Experimental Results

An AF-coupled structure of CoPtCrB/Co/Ru/Co/CoPtCrB was prepared on a 50 nm Cr metal substrate. The ferromagnetic films of CoPtCrB were $Co_{68}Pt_{12}Cr_{20}$ alloy doped with 5 atomic percent (at. %) B. The lower CoPtCrB film was 10 nm thick and the upper CoPtCrB film was 5 nm. The two ferromagnetic films were interleaved with a Co(0.5 nm)/Ru(0.6 nm)/Co(0.5 nm) trilayer that coupled the CoPtCrB films antiferromagnetically so their moments were oriented antiparallel. The thickness of the CoPtCrB films was chosen such that there would be essentially zero magnetic field at a predetermined distance above the magnetic layer. This distance is the height above the disk where the read head is located (i.e., the nominal flying height of the read head). Since the upper film 22 (see FIG. 1) is closer to the read head, the field from it will be higher than the field from the lower film 24. Thus the thickness of lower film 24 is made thicker to compensate and make the net field essentially zero at the head.

The magnetization of this structure was then measured with a Kerr looper over a range of external applied magnetic fields. A very high magnetic field (e.g., 8 kOe) sufficient to overcome the antiferromagnetic coupling of the two ferromagnetic films was first applied in the negative direction, and the Kerr data showed that the ferromagnetic films had their moments aligned parallel with the applied field direction. The field was then reduced and the Kerr data showed one of the ferromagnetic films switching magnetization direction, near the field strength that would correspond to the antiferromagnetic coupling field, so that the ferromagnetic films then had their moments aligned antiparallel. As the field passed through zero toward a positive applied field the ferromagnetic film moments remained antiparallel until the positive field exceeded the antiferromagnetic coupling field, at which point the ferromagnetic film moments became oriented parallel to one another and aligned with the positive applied field direction. Thus the Kerr data showed that this film structure is a synthetic antiferromagnet.

Next, this structure was bombarded with N+ ions at a dose of 2×10^{16} ions/cm^2 at 700 keV energy. When the structure was once again exposed to the same range of external applied field the Kerr data showed no AF-coupling of the ferromagnetic films. Instead the structure behaved like a single ferromagnetic layer, indicating that the ion bombardment had destroyed the antiferromagnetic coupling across the Ru spacer film. One can thus conclude that the ion bombardment had disrupted the interface between the Ru spacer film and the ferromagnetic films and intermixed the Ru with the adjacent ferromagnetic films. The structure had full remanence and a coercivity of about 1500 Oe.

Patterning of this same type of AF-coupled structure was then demonstrated using N+ ions. A 10 μm$\times$10 μm area of this structure was exposed to a dose of 6×10^{15} N+ ions/cm^2 through a Si stencil mask with micron size oblong-shaped holes. After patterning, the structure was first magnetized with a large magnetic field (20 kOe) in one direction. This field strength is sufficient to align the magnetization of the non-irradiated regions and to overcome the AF-coupling field in the non-irradiated regions so that the magnetizations of the ferromagnetic films in the non-irradiated regions are aligned parallel to one another and to the applied field. This field was then removed, which caused the two ferromagnetic films in the non-irradiated regions to become AF-coupled. Next, a field of 2 kOe was applied in the opposite direction. This 2 kOe field is less than the AF-coupling field of the non-irradiated regions but large enough to switch the magnetization direction of the ferromagnetically coupled films in the irradiated regions only. FIG. 3 is a magnetic force microscopy (MFM) image of the patterned structure, with the oblong-shaped regions being the irradiated regions where the Ru spacer film in the structure was disrupted so that the ferromagnetic films in these oblong-shaped regions are ferromagnetically coupled. The light and dark contrast lines on the long edges of the oblong-shaped regions originate from magnetic transitions between the top (or bottom) ferromagnetic film in the non-irradiated AF-coupled regions and the ferromagnetically coupled films in the oblong-shaped irradiated regions.

The two bit states in the recording media according to the present invention, wherein the magnetic field strength above the disk at the height where the recording head is located is essentially equal for the two films 24, 22, are depicted schematically in FIGS. 4A–4B. The magnetic transition regions are designated 80, 82. In FIG. 4A, only the transitions between the top film magnetic states, 70–72 and 72–74, contribute to the signal S1 because the bottom film magnetic states, 71–73 and 73–75, do not have magnetic transitions in the regions 80, 82. In FIG. 4B only the transitions between the bottom film magnetic states, 71–73 and 73–75, contribute to the signal S2 because the top film magnetic states, 70–72 and 72–74, do not have magnetic transitions in the regions 80, 82. In FIG. 4A the magnetization of the top ferromagnetic film 22 of the AF-coupled non-irradiated regions 70, 74 are oppositely aligned with the magnetization in the ferromagnetic irradiated region 72–73, leading to a typical magnetic field profile as indicated by S1. This represents one written state, a "1". Conversely, the other written state, a "0", is accomplished by applying a field larger than the coercivity of the ferromagnetic region 72–73 but smaller than the AF-coupling field between the top and bottom films 70–71 and 74–75 in the AF-coupled regions. In this way, only the ferromagnetic region 72–73 switches its magnetization and aligns parallel to the top films 70, 74. An inverted signal S2 is the result. The signals S1 (FIG. 4A) and S2 (FIG. 4B) depicted above the transition regions 80, 82 show that while the signs of the signals from the transitions are different, the amplitudes are the same, regardless of the directions of the transitions. This is because each of the ferromagnetic films 22, 24 is designed to have a magnetic moment so that the fields from the films, as detected at the head, are the same, even though film 22 is farther from the head.

If the alternative embodiment were used, where $Mr_1t_1=Mr_2t_2$ so that the layer 20 has substantially zero net magnetic moment, then S1 and S2 would have different amplitudes. This is because the two films 22, 24 would then have the same magnetic moments, but film 24 is farther from the head. Thus the signal S2 from the transitions in lower film 24 would have a smaller amplitude than the signal S1.

While the present invention has been particularly shown and described with reference to the preferred embodiments, it will be understood by those skilled in the art that various changes in form and detail may be made without departing from the spirit, scope, and teaching of the invention. Accordingly, the disclosed invention is to be considered merely as illustrative and limited in scope only as specified in the appended claims.

What is claimed is:

1. A magnetic recording medium comprising:

a substrate;

a magnetic layer on the substrate and comprising a first ferromagnetic film, a second ferromagnetic film, and a nonferromagnetic film between the first and second ferromagnetic films; and

wherein the magnetic layer is patterned into first regions with the first and second ferromagnetic films being antiferromagnetically coupled across the nonferromagnetic film, and second regions with the first and second ferromagnetic films being ferromagnetically coupled.

2. The medium of claim 1 wherein the first ferromagnetic film in the first regions has a thickness t1 and a magnetiza-

tion M1, the second ferromagnetic film in the first regions has a thickness t2 and a magnetization M2, and wherein the magnetic moment per unit area ($M2 \times t2$) is greater than the magnetic moment per unit area ($M1 \times t1$), whereby the magnetic field from the first regions is essentially zero at a predetermined distance above the magnetic layer.

3. The medium of claim **2** wherein the first and second ferromagnetic films are formed of substantially the same material, and wherein t2 is greater than t1.

4. The medium of claim **1** wherein the nonferromagnetic film is formed of a material selected from the group consisting of ruthenium (Ru), chromium (Cr), rhodium (Rh), iridium (Ir), copper (Cu), and their alloys.

5. The medium of claim **1** wherein the first and second ferromagnetic films are made of a material selected from the group consisting of Co, Fe, Ni, and their alloys.

6. The medium of claim **1** wherein the first ferromagnetic film includes an interface film consisting essentially of cobalt located at the interface of the first ferromagnetic film and the nonferromagnetic film.

7. The medium of claim **1** wherein the second ferromagnetic film includes an interface film consisting essentially of cobalt located at the interface of the second ferromagnetic film and the nonferromagnetic film.

8. The medium of claim **1** further comprising a nonferromagnetic underlayer located on the substrate between the substrate and the magnetic layer.

9. The medium of claim **1** further comprising a protective overcoat formed over the magnetic layer.

10. A magnetic recording disk comprising:

a substrate;

a nonferromagnetic underlayer on the substrate;

a magnetic recording layer on the underlayer and comprising a first cobalt alloy ferromagnetic film, a nonferromagnetic spacer film of a material selected from the group consisting of ruthenium (Ru), chromium (Cr), rhodium (Rh), iridium (Ir), copper (Cu), and their alloys formed on and in contact with the first ferromagnetic film, and a second cobalt alloy ferromagnetic film formed on and in contact with the spacer film, the magnetic recording layer being patterned into first regions wherein the spacer film has a thickness sufficient to induce the second ferromagnetic film to be exchange coupled antiferromagnetically to the first ferromagnetic film across the spacer film and second regions wherein the first and second ferromagnetic films are not antiferromagnetically coupled, whereby said second regions produce a magnetic field a predetermined distance above the magnetic layer that is greater than the magnetic field from said first regions; and

a protective overcoat formed on the magnetic recording layer.

11. The disk of claim **10** wherein the first and second ferromagnetic films of the magnetic recording layer are formed of substantially the same material.

12. The disk of claim **10** wherein the first and second ferromagnetic films of the magnetic recording layer are made of a material selected from the group consisting of Co, Fe, Ni, and their alloys.

13. The disk of claim **10** wherein the first ferromagnetic film of the recording layer includes an interface film consisting essentially of cobalt located at the interface of the first ferromagnetic film and the spacer film.

14. The disk of claim **10** wherein the second ferromagnetic film of the recording layer includes an interface film consisting essentially of cobalt located at the interface of the second ferromagnetic film and the spacer film.

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